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# THE MANAGEMENT OF THE PROCESS OF INNOVATION AND THE MEASUREMENT OF RESEARCH AND DEVELOPMENT PRODUCTIVITY

By
Thomas A. Barocci*, Anne Louise Averbach
Richard Anthony Ferraro and Kirsten R. Wever

W.P. #1373-82 January, 1983

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This report is one of a series under the aegis of the Productivity/Quality project within MIT's Sloan School of Management. The Project Director is Thomas A. Barocci, Associate Professor of Management. For further information contact Ms. Carolanne Foilb, Project Administrator, Sloan School of Management, MIT, 50 Memorial Drive, E52-454, Cambridge, MA 02139.

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# THE MANAGEMENT OF THE PROCESS OF INNOVATION AND THE MEASUREMENT OF RESEARCH AND DEVELOPMENT PRODUCTIVITY

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## TECHNICAL PROBLEMS; NON-TECHNICAL SOLUTIONS

American managers face three basic questions in dealing with Research and Development (R&D) productivity. First, what exactly is R&D productivity? Second, if you don't know what it is, how can you measure it? And third, if you can't measure it, how can you improve it? These questions look like they need technical solutions, so many managers are likely to wait for answers to come from further experience, or from the academic community. But in fact there are non-technical ways to solve these problems -- ways that managers can tackle directly to improve their companies' R&D productivity.

This paper examines the effects of R&D productivity through product and process innovation from basic research to development engineering and, finally, production. The actors in this game come not only from R&D departments, but also from marketing, manufacturing, and senior staff. The interrelations between these players is one of the most important determinants of successful R&D innovation and high productivity.

R&D is a process of innovation that begins with basic scientific research and goes through the stages of applied research, product and process development, and applications engineering. To begin with, R&D seeks facts and

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generalizations about science and technology. After these have become clear, engineering development translates them into specific and tangible results, ultimately to be embodied in a product or service. The typical conception of R&D as occurring primarily in the dust covered offices of mad scientists is misleading. At least as important to the outcome is the way scientific knowledge is applied to the practical aspects of the production of a saleable product.

The innovation process is a dynamic one. First, R&D (or marketing or a customer) comes up with ideas that might be applied to new products or processes, and presents these ideas or prototypes to the rest of the firm. Then marketing assesses whether the thing is too expensive, whether customers will want to buy it, and how it compares with competing products[1]. Finance will decide whether it's worth investing in. Manufacturing figures out if it can be built. Management or strategic planning considers how well the proposed innovation fits with the firm's strategic goals, whether the service organization is capable of supporting the project, and how much sense it makes to diversify in that particular direction. After having received all these inputs, R&D either scraps the project or goes back to the drawing board to modify it.

The process is dynamic and complex, but it has its rhyme and reason. To begin with, the locus of innovation shifts visibly and logically as the production process develops and process flows become more rational, tasks more specific, processes more capital-intensive, and product designs more

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[1]Von Hippel, Eric, "Get New Products from Customers," Harvard Business Review, March/April 1982.

standardized. As the process becomes increasingly defined, the focus shifts from R&D to production. This linkage is complex. The transition from R&D to the production floor will be one of the major emphases of this paper, since the success of the original R&D innovation depends crucially on how management and the firm's various units can help move a product from development to market.

R&D and innovation are integrally connected with the relationship between R&D, on the one hand, and marketing and manufacturing, on the other. How the process is managed has a great deal to do with how well all three departments communicate, both formally and informally, about the translation of the initial idea into its concrete form.

## BACKGROUND: THE MEASUREMENT OF PRODUCTIVITY IN R&D AND INNOVATION

R&D efforts used to emphasize creative freedom and the importance of research results for society as a whole. But over the last two decades the focus has shifted toward the satisfaction of market needs. The functions and orientations of research organizations are changing as well. Firms are increasingly concerned with market pressures and the need to sell their technology to users. This market orientation has the distinct advantage of providing R&D divisions with broad guidelines that help them make decisions about what projects to develop.

Thus, it is important to gather relevant information before a research project is launched. This can be made easier by calculating the business opportunity of each project before its development phase. Once a project has been approved and developed, it is also useful to evaluate it on the basis of how well it met initial objectives.

Whenever possible, R&D productivity measurement should be conducted at the project level. The project unit is self-contained, definable from beginning to end, and totally accountable for its work. When it is impossible to measure R&D productivity in this way, managers should be careful not to fall back on purely quantitative measures -- counts of things -- unless the results will really be meaningful with respect to the company's goals and strategies. But the use of measurements per se, no matter what kind, will have the advantage of communicating goals and strategies to lower levels of the firm.

Where do ideas originate? It is purely a matter of personal creativity or does social interaction have anything to do with it? Social contexts often provide so-called 'invisible colleges', where informal discussions generate learning, as well as ideas that are implemented after develoment in R&D. Invisible colleges are particularly important at the early stages of the innovation process (Allen, 1977).

But the manager's goal of fostering creativity must be tempered by the necessity to minimize risks. These two objectives often stand in practical contradiction to each other, since no firm will want to lead its industry in innovations while funding enough losing projects to lower overall R&D productivity (Urban and Hauser, 1980). To reconcile these competing objectives, the first step is clearly to identify an opportunity for some kind of new product or process development. This involves figuring out what market to enter and how to generate the ideas that could be the basis for entry. Subsequently, new ideas are evaluated and one or a few chosen.

One of the major problems with measuring productivity is that it is much easier to quantify inputs (e.g., labor and capital costs, computer resources, laboratory capital equipment) than outputs (e.g., technical drawings, engineering trade orders, proposals generated). (See Appendix A) This difficulty leads managers either to reject objective measurements completely

and focus their attention only on the qualitative nature of R&D efforts, or -- in a few cases -- to try to develop more meaningful quantitative measurement techniques. The second response is based on the common -- but questionable -- assumption that if measures are useful, it must be possible to translate them into hard numbers.

It can often be useful to estimate the financial effects of R&D endeavors. (See Appendix C for a list of five popular methods.) But the calculation of expected benefits is always hard. The tendency to defer this calculation indefinitely in order to collect more and more data can easily create inertia in the measurement process. Furthermore, it is also important to include both quantitative and qualitative data in these formulae. But making intangible projections on the basis of a combination of these different types of data is self-evidently difficult (Angwood, 1973).

The limitations of quantitative measurement techniques include the following: first, the results of R&D are intangible in an immediate sense; second, the nature of these results are unpredictable -- they could, for example, make a significant contribution to future projects, which could not be measured quantitatively; third, the time lag between a project's development and its completion is long enough that it is possible immediately to measure output, but not outcome; and fourth, measurements should address the qualitative aspects of trade-offs between the maximization of cost, schedule, technical and market requirements (Rocker, 1981).

Furthermore, common quantitative measures (e.g., the number of patents developed) cannot adequately catch the quality of R&D developments. Patents are important substantively only in an industry characterized by high levels of technological change, where advances are protected by trade secret status. Moreover, measuring the number of technical papers published by an organization or group indicates nothing about the relevance or technical

quality of those works. The number of lines of computer code generated by an R&D group says nothing about the efficiency or relevance of that material.

Firms traditionally measure the differences between planned and actual expenditures, technical performance and schedule performance. Since 'productivity' is the efficiency and effectiveness with which resources are used, it means nothing unless compared with the productivities of other firms or units, or with past performance. It is important to keep in mind the two-dimensional nature of the concept: productivity depends both on whether the final result was the desired one and on how much effort, energy and resources were sunk into attaining it. Each of these aspects is equally important, particularly for firms whose primary customer is the government, where it is necessary to meet technical goals on time and within budget. So financial measures of productivity are critical as a starting point. But their proper interpretation, and the utilization of qualitative measures as well, are the real challenges facing the managers of productivity.

Non-financial measurement techniques are both easier and harder, by virtue of their highly qualitative nature. They generally take into account project-specific characteristics, thus allowing for comparison over time, but not across projects. On the other hand, they can be combined with financial techniques, which allows for a more complete, though perhaps less specific, measurement of R&D productivity and innovation. But even when taken in isolation, non-financial measurements can be quite helpful in guaging overall trends: research indicates, for example, that the number of successful R&D-related and innovative ideas has increased over the last 26 years in the US. These findings reflect, among other things, an increased emphasis on funding early stages of R&D analysis. The days of list-making and brainstorming have given way to a more sophisticated process of business and market analysis (Booz, Allen and Hamilton, 1967, 1968, 1981).

Rating and ranking techniques provide a parallel or alternative approach to R&D productivity measurement. Check list approaches rank various factors going into the R&D/innovation process, thus taking into account some of the qualitative aspects of R&D that are so important to productivity. (See Appendix E for a description of two check-list approaches.) But it is important to distinguish between the measurement of R&D and that of innovation. Measuring R&D productivity alone gives no indication of the value of the output; the quality dimension can only be captured by measuring the innovativeness of that output. And the most valid types of evaluation are conducted among peers who have both technical expertise and familiarity with the substance of a given project. (See Stahl and Steger, 1977.)

In sum, productivity measurements appear to pose the dilemma of being too simple to be useful, or too complex to be useable. This is one of the primary hurdles management will encounter in the struggle to increase R&D productivity. The result is that it becomes all the more difficult to deal with the fact that you can't measure something you can't define, and you can't guage the improvement of something you can't measure.

It is clear, however that a successful project is likely to be characterized by:

- significant user involvement;
- ability to respond to market needs;
- appropriate mix of skills (Roberts & Frahmore, 1978);
- knowledge of users' needs;
- effective communication;
- effective marketing. (Project Sappho, 1977)

In the selection of a project the following things should be considered:

- marketability;
- product/company fit;
- marketing opportunity;
- product specialization. (Project Sappho, 1977).

## METHODOLOGY

Our study is based on four high technology firms, three of which produce primarily for the government. We administered a productivity interview to senior managers in each firm to find out about the company backgrounds, the programs and measurements used to guage and improve quality and productivity, the relations between labor and management, the degree of automation, employee particiation in productivity and quality programs, productivity incentive plans, and cost reduction programs. We paid particular attention to how these firms defined and measured productivity, to their management compensation and employee suggestion systems, and to training programs.

Our data on the specific activities of these enterprises derived from further interviews at various levels of each company. We asked senior management how R&D fit into the general corporate strategy. R&D managers were asked the same thing, as well as questions about their budgeting processes, departmental organization, interactions with other departments, how productivity is measured, and managerial control of R&D projects. Other personnel were asked about the new product development process and the evolution of recent successful developments. Marketing and manufacturing managers and engineering personnel were addressed on the issue of their relationship with R&D. (We conducted a total of 24 interviews: the major characteristics of the firms are shown in Figure 2.)

## CORPORATE CULTURES AND ATTITUDES ABOUT PRODUCTIVITY

Management style affects working conditions, and working conditions are critical to output. Thus, a company's culture, which shapes its management style, is of primary importance to its innovativeness and productivity.

The corporate environment should allow managers to understand the people who work for them, what they want, and how they are motivated. In R&D project development there are so many different functions and people involved that understanding these issues can become very complex[1].

At the beginning of the R&D process, someone has to generate ideas. This phase is intangible and difficult to bring about. One of the main reasons why managers have trouble at this stage of the game is that it is very hard to figure out how to motivate the scientists and engineers on whose creativity this process relies. But there are certain methods of staffing and particular organizational structures (discussed below) that are likely to succeed. And it should be kept in mind that the 'creative scientist' is not the only one involved in the process. Innovation requires the participation of a great many people, not all of whom respond to the factors that motivate scientific creativity.

There are five key staff roles in the process:

1) Creative Scientist
   - requires automony
   - works well alone
   - highly self-motivated

2) Entrepreneur
   - aggressive, energetic
   - sells the idea throughout the firm

3) Project Manager
   - practical organizer
   - plans of lead time, materials, support, personnel, etc.

---

[1]The growth rate and relative maturity of an industry will affect the stage of a firm's evolution from small, technology-based production to major high-volume production. The type of production affects the firm's culture as well as the nature of appropriate innovations. Product innovation (developing new and different models) is generally a response to expanding markets. Process innovation (cost-cutting in the production of existing products) is more usual. In a mature industry (e.g., machine tools), smaller, newer firms are more likely to innovate than larger and older companies. Firms have no direct control over these factors, but recognition of their implications for how to do R&D is critical to overall R&D productivity.

4) Project Sponsor
   - senior person
   - guides project along most effective path through organization

5) Gatekeeper
   - keeps lines of communication open between firm and environment and within firm
   - up-to-date on matters technical
   - maintains personal contacts within and outside firm

5a) Market Gatekeeper
   - provides R&D with information on user needs, competitors' positions, government regulations, etc.
   - identifies market trends (Roberts, 1977)

The maintenance of the proper balance between these five roles is one of the most important functions of R&D managers.

Motivation is an equally important aspect of successful project management. Managers often have short-term financial incentives that prohibit their involvement or interest in longer-term projects with no visible short-term revenue benefits. Senior scientists and engineers often lack a sense of urgency about their research, usually because they stem from academic backgrounds without market constraints. Motivation can be difficult when lines of authority are too long or too rigid, or when managers are afraid to take risks.

Probably the most important aspect of motivation is the need to understand what employees want, and how they can work most effectively. Scientists and engineers, for example, respond to very different sets of stimuli. (See Figure 1) Broadly speaking, scientists are more interested in their particular fields of study, while engineers focus more on the needs of the firm itself.

FIGURE 1: WORK GOALS OF RESEARCH SCIENTISTS AND ENGINEERS

| Work Goals: How important is it to you to: | % indicating goal is very important | |
|---|---|---|
| | Scientists | Engineers |
| - have the opportunity to help company increase profits | 28% | 69% |
| - gain knowledge of company management policies and practices | 19% | 60% |
| - work on projects you yourself have originated | 74% | 32% |
| - establish your reputation outside the company as an authority in your field | 84% | 29% |
| - publish articles in technical journals | 88% | 15% |

Source: T. Allen, Managing the Flow of Technology, MIT Press, Cambridge, 1977.

Further, the unique characteristics of all knowledge workers must be taken into account. These people:

- adapt easily to group settings;
- have the skills for problem solving and innovation;
- are highly self-motivated;
- possess a sense of self esteem; and
- require freedom in work environment and methods. (Gregerman, 1981)

An adequate awareness of these qualities allows for the kinds of employee-specific management techniques that are necessary to the enhancement of any type of productivity.

This section has emphasized the various disaggregated aspects of productivity in R&D and innovation. How those pieces fall together is the underlying question with which this paper concerns itself. And that question is primarily a management issue, having to do with organizational integration and integrity.

The following section is devoted to the description of our case studies. Company overviews appear in Figure 2. The text goes on to explain how the dimensions covered in these overviews combine to shape the R&D productivities of the four cases we consider.

Alpha

This research site is a corporate service division whose customers are the firm's six other divisions. Alpha considers the level of its technology to be its strongest competitive edge, with quality running a close second.

Decisions are made both by functional and project management. The firm is matrix-organized. The project manager is responsible for moving the project out the door; the functional manager updates techniques, ensures employee learning and sees that incrementally acquired knowledge is applied to future projects. Internal communication is sustained by shifting middle managers across divisions.

FIGURE 2: FIRM OVERVIEWS

| | Alpha | Beta | Gamma | Delta |
|---|---|---|---|---|
| SIZE | - FY 1980 sales; $160 mil. | - FY 1981 sales; over $500 mil. | - FY 1981 sales; $134 mil. | FY 1980 sales; over $100 mil. |
| PRODUCT | - Space Electronics | - Space and Military Electronics | - Strategic Electronics | - Bio-medical Instruments |
| CUSTOMER | - Primarily Government | - Primarily Government | - Primarily Government | - Commercial |
| PERCEIVED COMPETITIVE EDGE | - Technology<br>- (Quality) | - Technology<br>- (Quality, Service) | - Technology<br>- Research<br>- Quality | - Technology<br>- (Quality, Service) |
| MANAGEMENT TENURE | - 20 years and and over, upper and middle management | - Upper management up to 30 years | - Upper management over 20 years;<br>- Middle management about 20 years;<br>- Lower management about 15 years | - All levels between two and six years only |
| MANAGEMENT APPROACH TO PRODUCTIVITY | - Abstract recognition of need to improve productivity, but insufficient practical commitment | - Productivity considered a viable practical goal, especially with reference to quality, but government regulations constrain creative approach | - Intense productivity emphasis at all levels;<br>- Military specifications pose constraints but firm response is to try to diversify into commercial market | - No specific productivity focus, but firm estimates of slow improvement over past five years<br>- Productivity viewed only in financial terms |

While there is a strong degree of decentralization, generic divisional goals regarding quality, productivity and integration apply at every level of the division. Each sector is assigned a task force to integrate these goals. Quality is measured consistently; improvements are taken very seriously. On the other hand, an existing quality circle group is somewhat slighted by the division as a whole. And a recently established productivity function still occupies an obscure and tenuous position.

Productivity goals are built around projections of how long it will take for some product to be produced. Blue-collar workers are monitored as per government regulations, but at the three top management levels, Alpha believes that white-collar productivity is more important.

The definition of productivity is considered to be completely subjective. Nonetheless, the firm's strategy entails productivity enhancement, especially in the promotion of effective two-way communications (across divisional levels) and in maintaining challenging, achievable and measurable productivity objectives. But it is clear that these are still distant goals. The problems involved in measuring productivity have prevented this division from undertaking any great efforts to improve it. Like almost all firms, measurements are generally finance-based, emphasizing return on assets employed, financial forecasting, and so on.

But the firm perceives that if productivity is not as high as it could be, the problem is one of measurement. It is also acknowledged that customers (mainly the Department of Defense) are often averse to taking risks of the kind associated with the implementation of comprehensive productivity programs. Further, this division is hampered by the strict contracts that dictate many production methods and processes.

The attitude toward productivity is largely negative. According to our interviews, this seems to have mostly to do with the fact that when production standards are dictated, and when contracts include no incentives for increased productivity, it is hard to garner upper management enthusiasm for far-reaching and long-run efficiency programs.

Beta

This firm was started in 1946, and now has 30 divisions. Over the last five years, $1 billion has been spent on capital improvements and division expansions. Like Alpha, Beta competes primarily on the basis of technology. Quality is also important, followed by an emphasis on service. Price competition is relatively unimportant here, as it is in most high technology government-oriented enterprises.

The tenure of top and middle management is very long. The Chairman of the Board and the company president were around at the beginning, in 1947. But the organization has a heavy focus on bottom-up management. The emphasis is on providing an environment that keeps employees efficient and satisfied. There is a substantial amount of communication between divisions and corporate headquarters; conflicting goals are reconciled quickly and relatively effectively.

The corporate culture is that of a typical research organization. One division is purely involved in research, the others in product development. All depend on technical competence, charismatic organizational leadership, and cooperation across divisions. This leads the firm to be more involved in driving than forecasting technology.

Success is measured in terms of the number of competitive bids won, which hinges on technological leadership. There are no stockholders. Since the firm is privately owned, the only way it can grow is by generating profits. One advantage of being privately owned is that there are no short-term stockholder demands to inhibit investment in long-term projects. Profit measurements include both the percentage of sales and the percentage of assets employed. While divisions are compared on the basis of profits, their relative success is not measured in quantitative terms.

Unlike Alpha, Beta feels that productivity improvement is a viable corporate goal. The problems of measurement do not get in the way of this belief. Perhaps being privately owned accounts for Beta's ability to implement a longer-term focus, since there are relatively few constraints on taking chances that are likely to pan out only in the long-run. Furthermore, Beta is a bottom-up organization in which employees have a great deal of leeway, and in which customer satisfaction is of great importance. At every level, the organization demonstrates a serious commitment to the improvement of quality.

The firm has no specific productivity goals, though each of six groups has a productivity improvement plan. These plans are largely qualitative, applying mostly to white-collar workers, and emphasizing quality throughout.

Like Alpha, Beta is a government contractor; the two thus face many of the same constraints. However, while there are no specific productivity goals, Beta has attempted to incorporate a productivity improvement plan into each group. The idea is that if you improve quality, you are likely to improve productivity too as well.

Gamma

Gamma is a division of a large, diversified corporation; it develops products out of specialty materials, designed in-house, and builds electronic systems. Almost all of its contracts are with the government, so schedule pressures and cost parameters are vital. The organization is relatively rigid, in keeping with its government contract-orientation.

The emphasis of this firm is also on research. But it is currently beginning a full-scale production effort. Since this undertaking is still very new, a great deal of attention has been focused on it. The result has been a proliferation of new programs to improve productivity.

Of all the cases we examined, Gamma was the most interested in improving productivity, and the most willing to allocate the resources necessary to do so. Though military specifications often slow the introduction of a number of potential innovations, tremendous efforts are going into the improvement of certain systems within the firm.

To begin with, Gamma has very active quality circles and extensive personnel training programs. Perhaps even more important, Gamma is in the process of installing a manufacturing resource planning system (MRP). Among the benefits Gamma expects to attain through its MRP are the following:

> the facilitation of growth;
> improved responsiveness to schedule changes, programs and status;
> better use of management resources;
> better planning of priorities and capacities;
> delivery performance; and, last but not least,
> improved productivity.

The MRP effort runs deep. Twenty-five of Gamma's employees have learned how to use the software; twelve have been designated as trainers for the rest of the firm. The program is a thorough-going attempt to change the entire

nature of the company by rendering it more effective at program management. (The four major systems that are to be affected by the MRP are scheduling, materials, production and accounting.)

The division also has a training department with classrooms, special trainers, and a budget of its own. Employees are being educated about productivity enhancement, and plans for full divisional productivity programs are being drawn up.

One of the interesting aspects of Gamma's approach is that the emphasis is placed on the system, rather than on the performances of the individuals within it. This means the problem with individually-based measurements is to some extent avoided. None of these innovations would work, of course, without the whole-hearted support of top management. The esprit de corps at Gamma is high. Management is keenly aware of employees, and employees are generally very enthusiastic about their work.

R&D productivity is measured informally, on the basis of the number of government contracts won. As with Alpha and Beta, technological leadership is what keeps Gamma competitive. The primary research division is centrally located; communication channels are strikingly open. This division is more oriented toward product development than the above two companies. But like Alpha and Beta, it is organized by matrix.

Delta

We examined a division of Delta which produces health-related products, primarily patient monitoring devices. The division is physically distanced from the rest of the firm. Like the other cases, it competes on the basis of technology, quality and service, but not yet on the basis of price. The medical care industry is becoming more 'big business' oriented, so customers' requirements are increasingly cost- and service-related.

The managers in this division have been there only between one and six years. The tenure of all management levels is short. Decision-making is participatory, with each division focusing on meeting short-term profit objectives. The style is management by objective -- employees are thus able to provide input about company goals. Management is low key, placing great emphasis on hiring capable people who need little motivation or guidance. But while the motivation system is based on low-key management, there is a high level of internal competition. All employees set goals and are evaluated annually on their achievement of these.

Like the other cases in this study, Delta is technology driven. Division success rates are measured by profit and growth, and compared monthly. Productivity goals must be fit into short-term monthly objectives. But there is an overall emphasis on quality; quality-related data are collected and published monthly, which indicates to employees that management takes this goal seriously.

Delta has three major groups: marketing, manufacturing, and R&D. The lead group is unquestionably R&D, which is responsible for all business and long-term strategic planning. The firm is highly engineering-oriented. But while the main work of the division is product development, the atmosphere is R&D-oriented: employees are encouraged to be as innovative as possible, with compensation rewards linked to innovative work.

About 8 to 11% of all company revenues are returned to R&D. Still, there is no specific productivity incentive plan, no productivity function, and the firm receives no productivity newsletters or publications. Productivity (value of output) is measured formally only for non-exempt employees.

Delta's emphasis is on increasing the productivity of its engineers. One of the reasons why a premium is placed on this occupation is that there is a projected decrease in the number of trained engineers to enter the market over the next few years. To deal with this problem in a preemptory fashion, Delta has an MRP system that compares similar kinds of projects. When productivity is higher in a given project than in the previous one, engineering productivity is considered to have improved.

That, however, is the extent of Delta's productivity focus. It is estimated that labor productivity in general has been raised by about 30% per year over the last five years, but these guesses are based purely on financial statistics.

The first formal objective is profit. If the return on net worth equals the sales growth rate, profits should be able to finance growth objectives. Corporate emphasis is on the creation of new products, but great attention is paid to short-term profit goals. Both of these circumstances are probably connected with the fact that this division is not dependent on government contracts which, once obtained, provide a longer-term horizon.

## THE SUCCESSFUL SELECTION AND DEVELOPMENT OF A NEW PRODUCT: LINKING R&D WITH MARKETING

One particular experience at Gamma provides a highly interesting example of the process by which a new product is shifted out of R&D and into full-scale development. The product (X) is currently going into production for the government (1982); the details of the development are still easy for everyone to recall. And the process was particularly well thought-out, despite the fact that it took 15 years for the product to be accepted in the market.

It was projected that X has a good chance of going commercial by the end of this decade. The possibilities for commercial production was examined by sales people who established contact with and presented various ideas to potential non-governmental customers.

After designing the project, Gamma launched a concerted marketing effort to get X accepted by the industry. This effort included winning a particular industry award, advertising in relevant magazines, and making various prototypes available to potential customers for examination, testing and feedback.

Once the government demonstrated interest in the further development of X, the firm made a conscious effort to meet the government's specific needs and wants. It was publicized that X could be produced in various forms, depending on customer preferences. When X was introduced on the market, the firm accumulated a list of various industries and government agencies that might be interested. The next step was to establish trade marks. Customers were notified of the firm's progress all along the way.

One key component of X's initial success was the fact that Gamma established excellent relationships with suppliers. There was also a very close link between the marketing and technical efforts involved in the development of X. It is particularly important for Gamma to keep an eye on private product markets because, as a government contractor, the firm's business is susceptible to political priorities. Gamma is carefully developing non-governmental markets to smooth over any rough swings in government expenditures.

The process by which X was developed illustrates how it should be done. Perhaps most important is the firm's willingness to learn from past mistakes, and to respond first and foremost to the market. Of course the reasons for X's developmental success are manifold. But at base, it could not have been done without a great deal of management skill and tenacity.

The connection between R&D and marketing is becoming increasingly important to all firms. The example of Gamma's experience with the development of product X illustrates how effective cooperation between the two is critical. But it is not always easy to achieve that sort of cooperation between different functional groups. Friction can arise from a number of circumstances, including mutual task interdependencies, task-related asymmetries, differences in reward criteria, functional specialization, dependence on common resources, and ambiguities in role descriptions and expectations (Souder and Chakrabarti, 1978). But a high degree of interaction and information exchange between R&D and Marketing is a major prerequisite for both commercial and technical success. The effectiveness of the integration between the two realms depends most importantly on whether or not they use joint reward systems and/or the degree to which the integration is formally legitimized.

It is interesting to consider some of the factors that are <u>not</u> very important to a product's successful transition from R&D to production. Innovation does not appear to be circumscribed primarily by R&D capabilities or technical opportunities. It is not necessary for R&D to be represented in a firm's long-range planning in order for successful innovation to occur. (This may, in fact, be a comment on the generally mediocre nature of many companies' long-range planning methods!) And finally, the presence of environmental uncertainty may be unconnected with the success or failure of product development.

Much more important are a firm's understanding of specific user needs and a concerted focus on marketing (Project Sappho, 1977). But these two factors alone do not guarantee success. Successful innovations are more efficient, but not necessarily speedier, than failures. Success often also requires the use of outside technology and scientific advice. And workable projects are most often managed by a single senior person with relatively comprehensive authority.

The role of the user cannot be overemphasized. One study concluded that in 81% of the examined cases of major innovation improvement, it was the user who perceived a need for advanced instrumentation, invented the process, built a prototype, applied it, and diffused information on the value of the advance. Not all users are innovators; often users and manufacturers both claim responsibility for a new development (von Hippel, 1976). But more important is the fact that industries in which users do a lot of the innovating must be treated differently than sectors in which primarily manufacturers innovate. Where user information is valuable, special sales forces should be established, marketing research should take user input into account, and channels of information should be established in such a way as to use this information efficiently (Klein, 1981). (There are of course other reasons why a firm should gain a clear and comprehensive understanding of the market in which it operates, not the least of which is the fact that R&D and innovations must respond much more to market pressures today than they did twenty years ago.)

Alpha, Beta and Delta were relatively unequipped or unprepared to manage the development process as successfully as in the case of Gamma's product X. Most of Alpha's space electronics technology is developed in-house. The emphasis on marketing is minimal. Of all the divisions in our study, Alpha has the weakest link between marketing and R&D, which could be highly detrimental in the long-run.

Beta is also in high technology electronics, and produces primarily (but not exclusively) for the government. But Beta is organized in such a way as to provide a strong link between R&D and marketing. Contacts are both formal and informal. Engineers are involved in sales calls, and marketing relies heavily on technical back-up. Bid decisions are made jointly by R&D and marketing. Still, in the company hierarchy marketing takes a back seat to engineering. The marketing department is small; it mostly facilitates the firm's other functions. While the importance of marketing is acknowledged, the division is customer-driven, and thus relies only slightly on marketing to find out what customers want.

Delta is purely a commercial enterprise, with the most active marketing department of our cases. But marketing primarily supports R&D. R&D plays a major role in business planning, which is fairly unusual but -- in this case -- also successful. The research emphasis of this firm makes it crucial for R&D to receive input from both marketing and customers. The channels of communication are both formal and informal, including bi-monthly meetings between the heads of R&D, manufacturing, and marketing. While engineering is clearly the lead function, it is predictable that the importance of the marketing group will increase as hospitals (the primary customers) become more business-oriented and price-conscious.

## THE LINK BETWEEN R&D AND MANUFACTURING

The relationship between R&D and manufacturing is equally vital, partly because it is easy for a project to lose momentum once it is transferred from R&D to production. But collaboration between R&D and manufacturing is important also in the interpretation of technical specifications, in decisions about the trade-off between product performance and producibility, in quality control, and in a host of other areas.

A model of the technology transfer process from R&D to manufacturing appears in figure 3. The process should begin well in advance of the actual transition, and should involve not only R&D and manufacturing, but also top management and marketing. The transition is extremely difficult to coordinate, partly because the direct overlap of labor activity is massive at this phase. One way to address this problem is to involve down-stream personnel in up-stream processes (design people in the R&D phase, etc.), in order to create a sense of general 'ownership' of the project. A senior researcher should also be involved in the development phase to assist with technical problems, to maintain momentum, and to gain a better understanding of how outputs are used (White, 1977).[1]

Another model of the innovation process is illustrated in Figure 4. This model identifies six stages of product development:

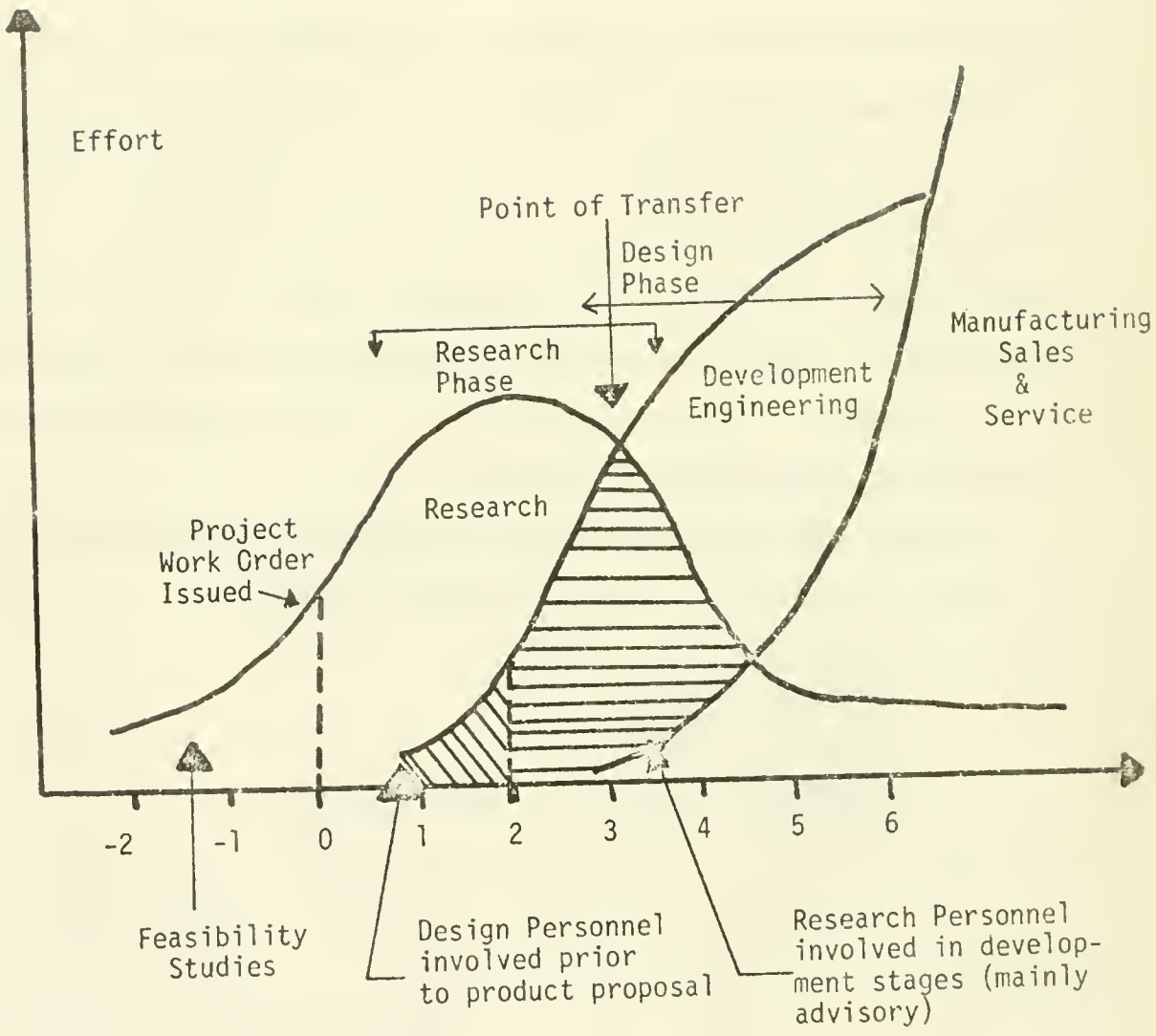
- recognition of opportunity;
- idea formulation;
- problem solving;
- prototype solution;
- commercial development; and
- technology utilization and/or diffusion.

There are clearly a lot of gaps to be bridged in this process. But appropriate organizational approaches can help. For example, product teams can tie R&D to the rest of the multi-functional organization, allowing the end product to embody the concerns of marketing, production and finance groups. This method also allows individuals all along the line to consider themselves a part of the project, and thus prevent inertia (Roberts, 1979).

---

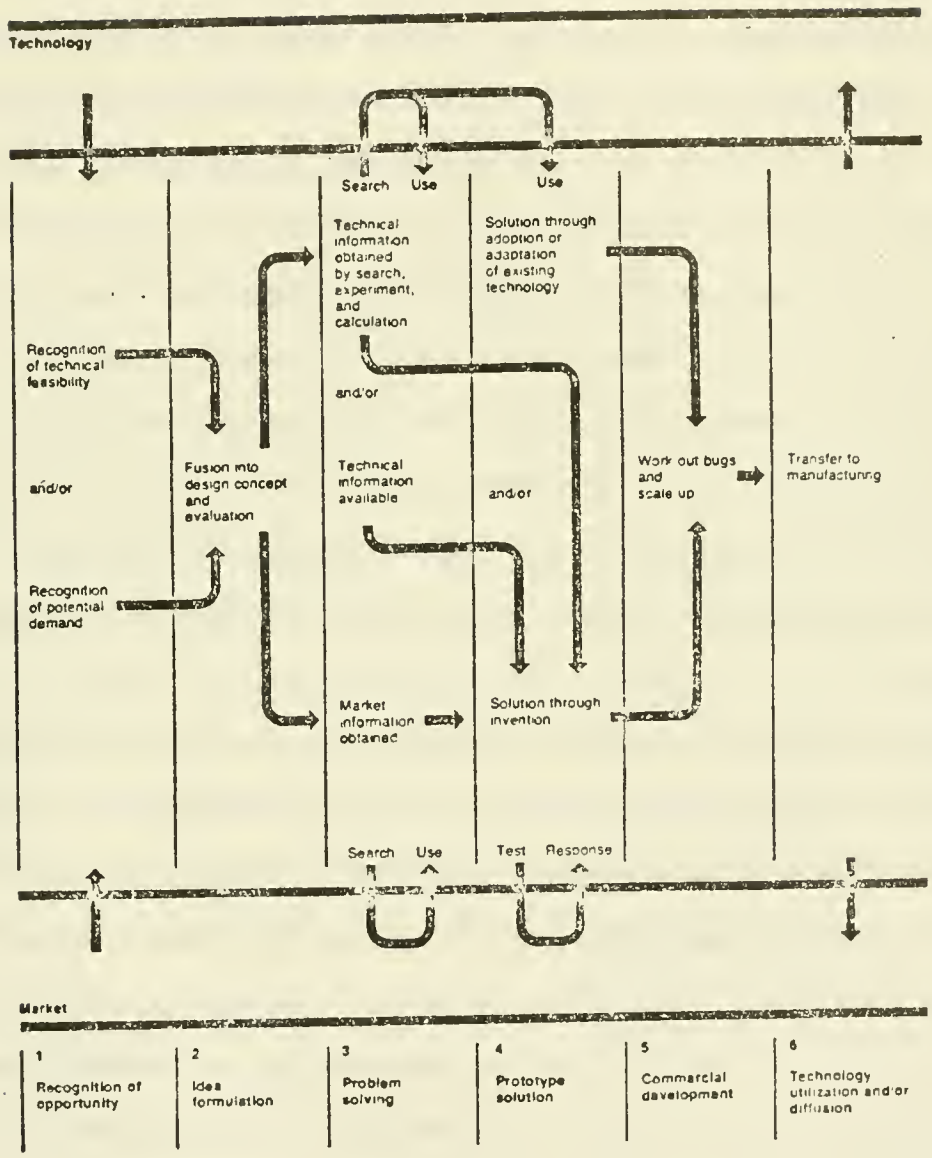
[1]Without a single leader, the transition can be dangerously haphazard. We suggest the formation of an autonomous group to facilitate the changeover, with one group leader reporting to top management.

FIGURE 3: TECHNOLOGY TRANSFER SCHEMATIC




Source: White, 1977

FIGURE 4: MODEL OF THE INNOVATION PROCESS




MODEL OF THE INNOVATION PROCESS. Interactions with the technology stream is shown at the top; interactions with market information is shown at the bottom.

Source: Roberts and Frohman

An alternate approach is to link R&D with the receiving unit through various joint efforts. Human Resource approaches can be very effective here, through the establishment of personal relationships across functional boundaries and the exchange of information, responsibility, and enthusiasm. Organizational integrators can help facilitate the transfer by having a foot in each 'camp.' Of course user involvement is equally important at this stage.

All of the managers we interviewed agreed that these gaps should be bridged, and that formal communication across functions should begin at an early phase of a product's development. Because of the importance of federal standards and specifications, government contractors pay most attention to assembly and test methods. But if standards are not incorporated in the earlier design phase, the transfer process is complicated even before assembly occurs.

The key to the transfer of information from development to production lies in the manufacturing engineering group, which interprets drawings and design specifications, and develops assembly and test procedures. Early involvement of this group significantly increases the chances for successful technology transfer.

At Beta the relationship between manufacturing and R&D is a loose one. The involvement of manufacturing engineering occurs only at the last stages of the product's development, just before full-scale production. Manufacturing engineering also has to deal with an inherent lack of concern on the part of production personnel for the technical aspects of its products. The need for increased communication is blatant. Another set of problems arises from the fact that the production department is many-faceted; each group requires different handling.

Not only does the manufacturing department fail to understand many up-stream functions, but people not directly involved with production also have trouble figuring out the manufacturing process. Specifically, managers and designers are on the whole poorly educated about the practical implications of the projects they develop.

At Alpha, R&D and manufacturing are linked formally through the manufacturing engineering group. The link is apparently quite successful. One of the reasons for this strong connection is doubtless that A operates under relatively intense schedule presures, thus requiring a clear definition of responsibilities. Manufacturing engineering is involved in project proposals right from the start. After a contract is let, manufacturing engineering becomes involved in the contract team. Every drawing must be approved by, and every product tested in the presence of, manufacturing engineering personnel. At a certain point the product designer is assigned to a new project, and replaced by a manufacturing engineer. Manufacturing employees have many reasons for wanting to become involved at early stages of the game; design engineers often approach manufacturing engineers informally to provide advance knowledge of a product's design and to gleen input from the production perspective.

Managers at Alpha also recognize the need for an up-stream information flow; manufacturing and test engineers are involved in process and equipment upgrades.

Gamma is in the process of diversifying into higher volume production, which will require computerized production scheduling. To meet this projected need, a fully integrated software package is currently being installed. (Management is also backing an intensive drive to increase white collar productivity.) The question is how the integration of this computer system will affect the relationship between manufacturing and R&D. It will be

important for users thoroughly to master the new system if they are to avoid information bottlenecks that could damage the interface between the two.

This potential hitch raises a larger issue that applies to all the firms in our study. CAD/CAM systems are becoming increasingly popular in a number of industries -- particularly in high technology sectors. These systems can help, but they can also hinder technology transfer to manufacturing. For instance, CAD/CAM could reduce the level of human interaction that currently appears to be necessary for an effective transfer.

The above discussion leads to several general prescriptions regarding the transfer process:

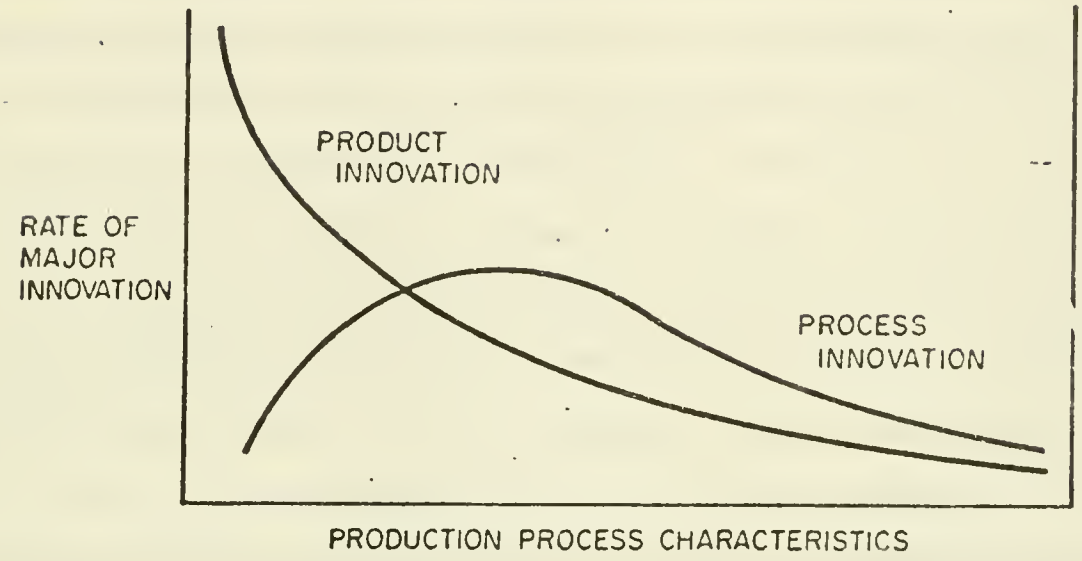
- Make sure receiving employees are involved early in project development;
- Let manufacturing personnel help with product design;
- Allow for two-way communications, with up-stream and down-stream information flows;
- Let people at all stages of the project's development feel equally involved.

## A THEORETICAL DISCUSSION OF THE RELATIONSHIP BETWEEN R&D AND MANUFACTURING PRODUCTIVITY

R&D affects manufacturing productivity; manufacturing affects R&D productivity. Their circular interaction is the concern of this section. R&D productivity is the effectiveness and efficiency of the innovation process, but there is an important distinction to be made here, between the productivity of doing R&D, and the effect of R&D on the firm's overall productivity. The question we address here is how R&D can enhance the business productivity of the firm as a whole.

Figure 5 illustrates the dynamics of product and process change. In established industries process innovations are more important. Different patterns of innovation can be observed by measuring the rate of innovations in various productive units (Abernathy and Utterbach, 1975).

FIGURE 5: THE DYNAMICS OF PRODUCT AND PROCESS INNOVATIONS




Source: Abernathy and
Utterback

Each productive unit is in one of three stages. First, a fluid pattern of innovation denotes frequent changes in product design in response to customer needs. Production is generally small-scale in this phase, since rapid adaptation is necessary. Second, the transition stage is a response to demands for increasing specialization through automation. Finally, the specific pattern is dominated by the manufacturing process, with emphasis on cost reduction through incremental changes in equipment and processes. The evolution of the productive unit through these phases entails a shift in the role of R&D. In the fluid pattern, the R&D focus is on product performance. Later on, the emphasis shifts to process innovation, leading to cumulative productivity advances (Headley, 1976 and Lloyd, 1979).

Increasing awareness of the effects of R&D and engineering on overall productivity throughout these phases is likely to result in changes in R&D organizations. As the focus shifts from product to process innovation, R&D efforts will increasingly center around process development, rather than product change. The effort to produce at lower cost will increase as competition becomes stiffer in high technology industries. The shift from product to process-orientation must be paralleled by a change in management focus to accomodate that dynamic.

The relationship between R&D productivity and manufacturing productivity reflects this shifting process. When the emphasis is on the product's performance, the level of R&D productivity is relatively high. Later, as the focus changes to manufacturing productivity, R&D productivity increases. Finally, in the specific stage R&D productivity is comparatively low, and only incremental advances occur.

The main point of this dynamic conception of the process is to illustrate that R&D does not function in isolation. R&D productivity depends in large measure on what happens in other units of the firm. The dilemma

presented by this notion is that there is a trade-off between R&D innovation capabilities and productivity gains: the conditions that support rapid innovative change are different from those conducive to high levels of production efficiency. How managers handle this trade-off will depend on how R&D is woven into the rest of the organization, and on how well R&D is able to keep in phase with other activities in the firm.

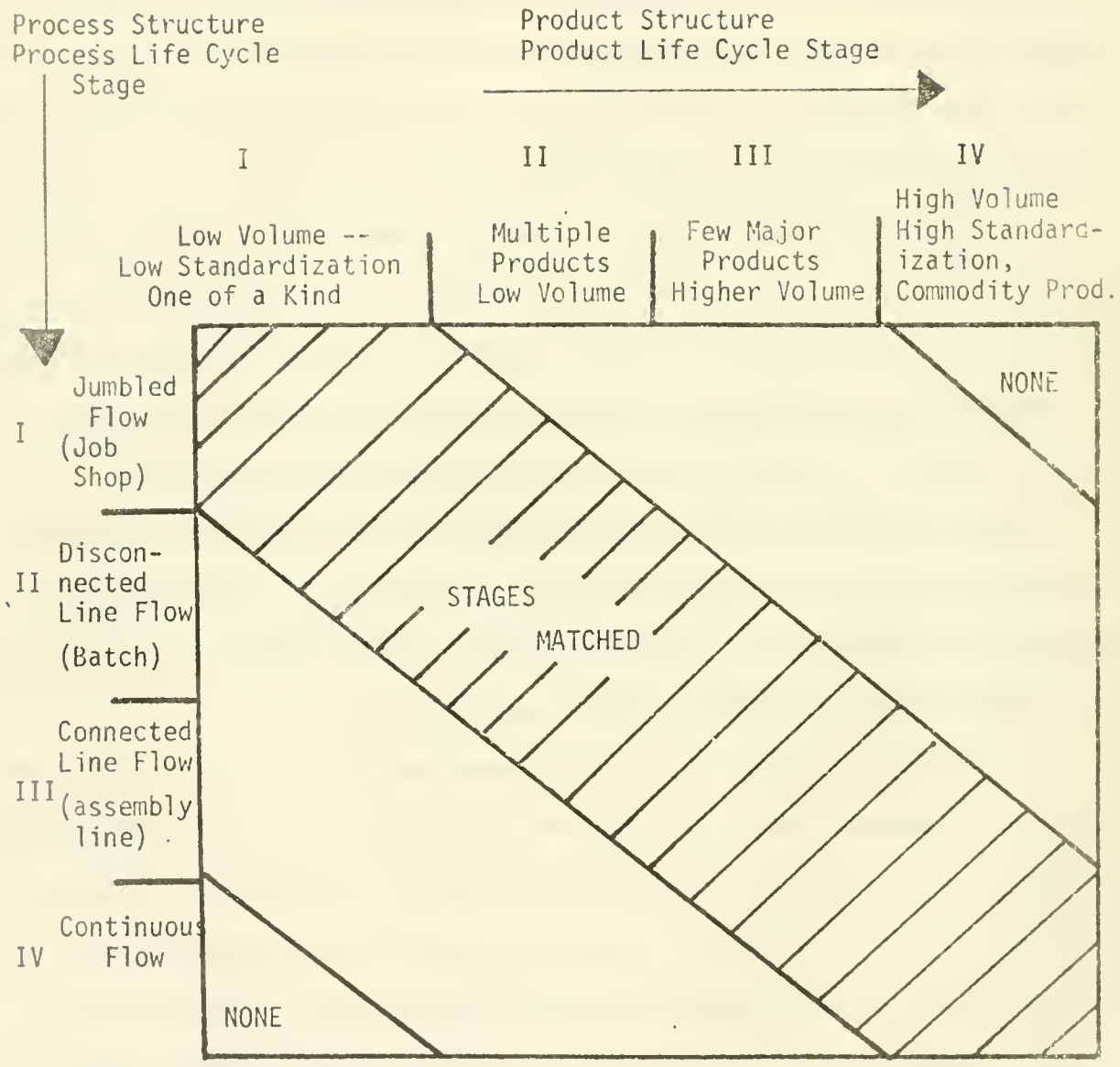
One way the trade-off can be minimized is by properly linking product and process life cycles. The roles of R&D and engineering are of course integrally connected with this link. A firm that choses to focus most heavily on innovation will have to give up some degree of profitability once the product reaches the mature stage of its life cycle. The dilemma is illustrated in figure 6. This trade-off has implications for the three firms in this study that are primarily government contractors. Manufacturers of nonassembled products (e.g., chemicals, glass, etc.) are more likely to focus on process development (Hayes and Wheelwright, 1979).

The need to integrate R&D with strategy, marketing and operations cannot be over-emphasized. Not only should managers pay attention to the different implications of product and process innovation, but they must also recognize that changes within a productive segment all feed on one another. While it is important to distinguish between the different effects of various factors on overall productivity, it is equally as vital to keep in mind that there is no analytic substitute for a well-integrated firm.

## CONCLUSION

We began by discussing how hard it is to define R&D productivity, and the resulting problems with measuring and improving it. Our most general and important conclusion is that people who work in and with R&D need to step back from their intense concerns with current individual obligations in order to

FIGURE 6:




Source: Hayes & Wheelwright

gain a broader perspective on the innovation process. This is the primary prerequisite for guaging R&D productivity realistically and holistically.

The importance of a holistic approach is made patently clear by the complex links between R&D on the one hand, and marketing, manufacturing, innovation and overall firm productivity on the other. Each of these relationships involves many distinct functions, groups of people, and managerial imperatives.

The cases examined in this study depend on traditional project management techniques. They measure technical performance. That is virtually the extent of their productivity programs. True, the measurement question is a tricky one. But some combination of quantitative and qualitative measures can still be helpful, particularly when organized around projects. One of the primary benefits of productivity measurement in R&D is that the very process broadcasts to all levels of the firm that managers are concerned.

Three most crucial considerations are to the successful management of innovations. First, the interfaces between R&D and marketing, and between R&D and manufacturing are equally important. The companies in this study had established better connections between R&D and marketing. The most important thing to remember about the R&D-manufacturing relationship is that it is necessary for people at all stages of the project's development to feel a sense of ownership of and commitment to it. Creating such an atmosphere is primarily a management issue; it can be approached in two ways: by transfering manufacturing personnel to project development, and by involving people from R&D or engineering in production.

Second, both formal and informal channels of communication across areas can be of value in ensuring project success. Informal channels are particularly conducive to the generation of ideas. Formal channels are necessary to sustained support of the kind of information exchange that is required for a project to reach fruition.

The final point is that at least three of these firms (Gamma might be an exception) could benefit from a better understanding of the factors that lead to project success. Among these are the product's relevance to the firm's main business, the size of the target market, the existence of a real need for the product, and its differentiation from other products on the market. Tying these issues together is the responsibility of top management.

More concretely, R&D managers should keep the following points in mind:

> R&D personnel should take a broad and holistic view of the innovation process, considering more than their own functions and roles;
>
> Imperfect measurements are better than no measurements at all, especially when applied to projects;
>
> The R&D/manufacturing interface and the R&D/marketing interface are equally important;
>
> Formal and informal channels of communication are equally important;
>
> Product success requires:
> product relevance,
> product/firm fit,
> adequate target market, and
> product differentiation.

Managers deal on a daily basis with one particular link between the processes and functions that play into R&D productivity and innovation. Only rarely does the opportunity present itself to conceive of the grander scheme of things. The problem is compounded by the fact that the development of new products and processes is an iterative process, constantly involving the interaction between R&D and other departments. R&D has certain needs; other departments do too. So their relationships are frought with constraints. The manager who has to deal with them day in and day out has a hard time avoiding the myopia that blinds him/her to the larger process. But it should be evident by now that the maintenance of a broad perspective is the R&D manager's primary ongoing task.

The firms in this study place little formal emphasis on R&D productivity enhancement. But that's not the main problem. Rather, they are more severely limited by interdepartmental, i.e., internal organizational, constraints which cannot be addressed with technical productivity- or measurement-related solutions. But if managers view the problem in non-technical terms, they will find that many of their technical problems can be overcome. More importantly, they will come to understand how organizational integrity can contribute to productivity in R&D, in innovation, and in the firm as a whole. This then offers them an exit from the dilemma of not being able to measure what cannot be defined, or to improve what cannot be measured.

## APPENDIX A

## R&D INPUTS AND OUTPUTS

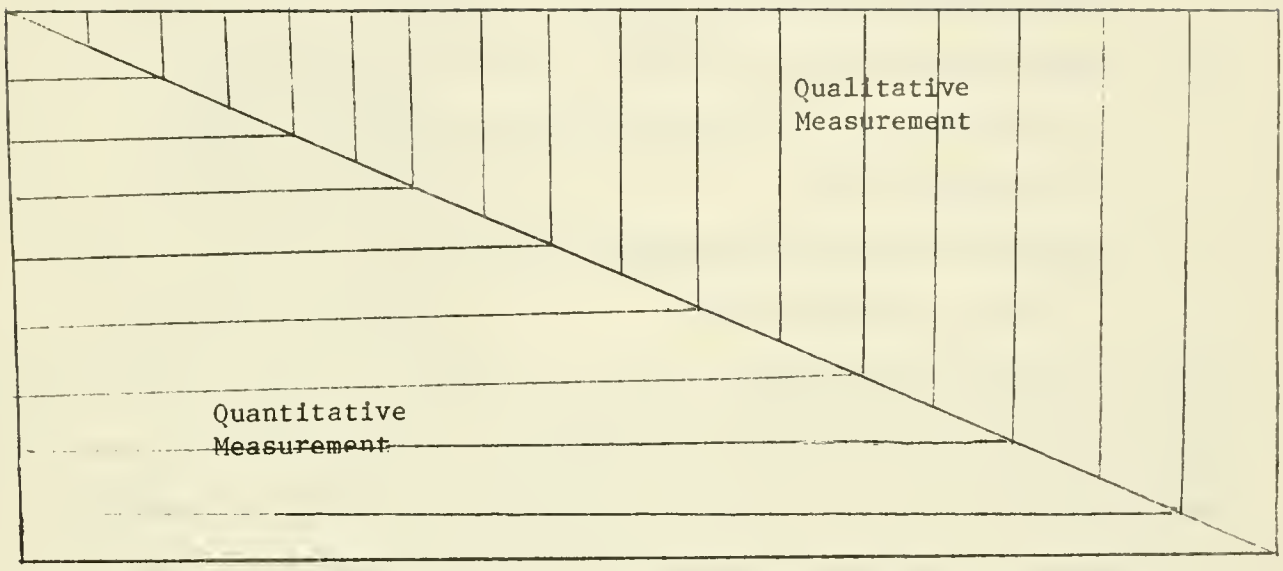
### INPUTS

$ (labor)
$ (capital)
employees
employee-dollars
labor hours, man-days, man-weeks
computer resources
laboratory capital equipment
technical library resources
technical travel resources

### OUTPUTS

profits
sales
new product sales
technical drawings
lines of computer code
new product/process prototypes, ideas, concepts
number of manufacturing problems solved
engineering change orders
bills of material
proposals generated
proposals won
patents
literature citations
awards
technical papers published, presented

APPENDIX B




Increasing level of complexity,
uniqueness, and abstractness.

The use of more qualitative techniques to measure R&D productivity as tasks change from simple, repetitive and well defined to complex, unique and more abstract.

Source: Ranftl, et.al.

## APPENDIX C

## FINANCE/BASED MEASUREMENT INDICES

A) Divide pre-tax earnings during a five year period by relevant R&D expenditures. (Schainblatt, 1981)

B) Compare pre-development estimates with actual results of:

- three year pre-tax earnings
- development costs
- ratio of the above two factors
- actual development time
- staff months required

C) Divide expected benefits by R&D costs.

D) Judge expected captial and operating costs of a future commerical venture to estimate financial return on investment; result is a discounted cash flow return to measure profitability of the venture. (Link R&D with other functions, particularly marketing, to establish accurate sales forecasts.)

E) Create an index on the basis of the equivalent maximum investment period, during which the maximum debt would be outstanding if a given project were undertaken. (Does not take into account cash flows after breakeven.)

## APPENDIX D

## NON-FINANCIAL MEASUREMENT INDICES

A) (Prototype developed in a military think tank) Assign divisions, branches and staff members scores on the following dimensions:

- product quality
- project timeliness
- manpower utilization efficiency
- computer utilization efficiency
- project priority

Then distribute productivity points back to the units measured, including individuals.

B) Compare staff months spent on completed projects; tie the timing of the measure to the specific individual or unit being measured, taking into account the level of difficulty of the project. (Take care not to end up with a measure of resource requirements, rather than changes in productivity.) (Impossible to compare results across projects.)

C) Survival function technique: Measure probability of success for research tries, including financial estimates of profits and R&D expenditures. This method can reflect firm-specific strategies/goals. (Problems: difficult to apply multiple chance efforts to non-repeatable projects; hard to measure benefits; cost-benefit relationship excludes capital investments.) (Angwood, 1973)

D) Plot the number of <u>ideas</u> over time to understand evolution of a project through the following stages:

- exploration
- screening
- specification
- development
- testing
- commercialization

## APPENDIX E

## RATING AND RANKING TECHNIQUES

A) Checklist Approach: Rank how important various elements in the proces are to its success. (Takes into account the multifaceted nature of R&D productivity.)

B) Quantified Checklist: Weight factors (see supplied list) and calculate project rating from sum of descriptor and element weights, divided by the latter. (Dean, 1958; Kepher and Tregoe, 1965)

Note: Weighted sums don't necessarily provide significantly different measures than unweighted sums. See the results of a study by Stahl and Roser (1978), below:

| Output mean ranked (by scientists and engineers) | Outputs ranked in order of importance by weights (from supervisors) |
|---|---|
| 6 | 1. Technical reports |
| 4 | 2. Computer codes |
| 5 | 3. Procurement packages (contract monitoring) |
| 1 | 4. Technical presentations |
| 2 | 5. Evaluations of proposals (contract monitoring) |
| 3 | 6. Management presentations |
| 7 | 7. Work unit planning documents (proposals to management) |
| 8 | 8. Journal articles |

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